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# COLLISIONLESS DAMPING OF SURFACE PLASMA OSCILLATIONS AND POSSIBILITIES OF ITS REVERSE AT THE INTERACTION WITH CHARGED PARTICLE FLOWS

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This paper is devoted to investigation of the interaction between the charged particle flows passing through the boundary of plasmalike media and surface oscillations.

Suppose that an external flow of charged particles crosses the boundary between the media of different electromagnetic properties, for example, dielectric (vacuum)-semiconductor. Let a semiconductor occupy the space region $y > 0$ and vacuum (dielectric with $\varepsilon_1$) is at $y < 0$. It follows from Maxwell's equations that there are the surface electromagnetic oscillations with spectrum

$$q^2 = \frac{\omega^2}{c^2}\frac{\varepsilon_1\varepsilon_2(\omega)}{\varepsilon_1+\varepsilon_2(\omega)}; \quad \varepsilon_2(\omega) = \varepsilon_0 - \frac{\omega_0^2}{\omega^2}; \quad \varepsilon_2(\omega) < 0, \quad \varepsilon_1 > 0, \tag{1}$$

where $\omega$ is the frequency of plasmon, $\mathbf{q}$ is the wave vector along the surface, $\omega_0^2 = 4\pi e^2 n_0/m$ is the plasma frequency; $n_0$ is the electron concentration, $m$ is the effective mass of electron. If $c \to \infty$, the dispersion law is $\omega = \omega_0/\sqrt{\varepsilon_0+\varepsilon_1}$.

Hamiltonian of the system has the following form:

$$\hat{\boldsymbol{H}} = \hat{\boldsymbol{H}}^{(F)} + \hat{\boldsymbol{H}}^{(e)} + \hat{\boldsymbol{H}}^{(\mathrm{int})}, \tag{2}$$

where $\hat{\boldsymbol{H}}^{(F)} = \frac{1}{2}\sum_q \hbar\omega_q\left[\hat{a}_q^+(t)\hat{a}_q(t) + \hat{a}_q(t)\hat{a}_q^+(t)\right]$ is the Hamiltonian of electromagnetic field (surface plasmons), $\hat{\boldsymbol{H}}^{(e)} = \sum \mathcal{E}_k \hat{b}_k^+(t)\hat{b}_k(t)$ is the Hamiltonian of an electron system; $\mathcal{E}_k = \hbar^2 k^2/2m$ is the dispersion law of electrons; $\mathbf{k}$ is the wave vector of the electron; $\hat{a}_q^+(t) = \hat{a}_q^+\exp(i\omega_q t)$, $\hat{a}_q(t) = \hat{a}_q\exp(-i\omega_q t)$, $\hat{b}_k^+(t) = \hat{b}_k^+\exp(i\mathcal{E}_k t/\hbar)$, $\hat{b}_k(t) = \hat{b}_k\exp(-i\mathcal{E}_k t/\hbar)$, $\hat{a}_q^+, \hat{a}_q, \hat{b}_k^+, \hat{b}_k$ are the birth and annihilation operators for the plasmons and the electrons in the states $\mathbf{q}$ and $\mathbf{k}$;

$$\hat{\boldsymbol{H}}^{(\mathrm{int})} = \sum_{kqk'} W_{kqk'}\hat{b}_k^+(t)\left[\hat{a}_q(t) + \hat{a}_{-q}^+(t)\right]\hat{b}_{k'}(t) \tag{3}$$

is the Hamiltonian of the electron-plasmon interaction.

To find the expression for the matrix element $W_{kqk'}$ it is necessary to use the expression

$$\hat{\boldsymbol{H}}^{(\mathrm{int})} = -\frac{1}{c}\sum_{\alpha=1}^{2}\int \hat{\mathbf{j}}(\mathbf{r},t)\hat{\mathbf{A}}_\alpha(\mathbf{r},t)d\mathbf{r}, \tag{4}$$

where

$$\hat{\mathbf{j}}(\mathbf{r},t)=\frac{e\hbar}{2m_0V}\sum_{k,k'}(\mathbf{k}+\mathbf{k}')\hat{b}_k^+(t)\hat{b}_{k'}(t)\exp i(\mathbf{k}'-\mathbf{k})\mathbf{r}$$

is the operator of an electron current density,

$$\hat{\mathbf{A}}_\alpha(\mathbf{r},t)=\sum_q\left(\frac{4\pi\hbar c^2}{V\omega_q}\right)^{1/2}\mathbf{e}_\alpha\left[\hat{a}_q(t)+\hat{a}_{-q}^+(t)\right]e^{i\mathbf{q}_\alpha\mathbf{r}}$$

is the operator of the vector-potential of the surface wave electromagnetic field; $\mathbf{e}_\alpha$ is the unit polarization vector: $e_x=e_{1x}=e_{2x}=(q_x/|q|)\sqrt{L|q|/(\varepsilon_1+\varepsilon_0)}$, $e_{1y}=-e_{2y}=ie_x$, $e_z=(q_z/q_x)e_x$, $\mathbf{q}_{1,2}=(q_x,\mp q,q_z)$, $V=LS$ is the volume of the interaction space, $S$ is the cross-section of the sample.

Carrying out the standard procedure [1,2] we obtain the following kinetic equation which describes the change of the surface plasmon number $N_q$ as the result of their radiation and absorption with the electrons $n_k$

$$\frac{\partial N_q}{\partial t}=\frac{2\pi}{\hbar}\sum_{k_1k_2}\left|W_{k_1qk_2}\right|^2\left[(N_q+1)n_{k_1}(1-n_{k_2})-N_qn_{k_2}(1-n_{k_1})\right]\delta(\varepsilon_{k_1}-\varepsilon_{k_2}-\hbar\omega_q), \quad (5)$$

where [2]

$$W_{k_1qk_2}=\frac{q_x(k_1^2-k_2^2)}{m_0L|q_x|\left[q^2+(k_{1y}-k_{2y})^2\right]}\left(2\frac{\pi e^2q\hbar^3}{S\omega_q(\varepsilon_0+\varepsilon_1)}\right)^{1/2}. \quad (6)$$

From here for $N_q>>1$ we obtain the expression for the decrement or increment of the surface plasmons, $\gamma=(1/2)N_q^{-1}(\partial N_q/\partial t)$.

Suppose that injected electron energy is distributed near some value $\varepsilon_{k0}=p_0^2/2m_0=\hbar^2k_0^2/2m_0$. Then one can present the electron number $n_k<<1$ as

$$n_k=\frac{n_{0b}(2\pi\hbar)^3}{(2\pi m_0T)^{3/2}}e^{-\frac{\hbar^2(k_y-k_0)^2}{2m_0T}}e^{-\frac{\hbar^2(k_x^2+k_z^2)^2}{2m_0T}}, \quad (7)$$

where $n_{0b}=\sum n_k/V=\int n_k\,d\mathbf{k}/(2\pi)^3$ is the density, $T$ is the temperature of the electron beam.

Taking into account the conversation lows and the conditions $P_0^2/2m_0>>\hbar\omega_q$, $P_0^2/2m_0>>T$, $\omega_q/v_0>>q$, we obtain

$$\left|W_{k_1qk_2}\right|^2=\frac{8\pi e^2q\hbar v_{y1}^4}{VL\omega^3(\varepsilon_0+\varepsilon_1)}. \quad (8)$$

If the condition $T>>\hbar\omega_q$ is fulfilled one can consider that $n_{k_1}-n_{k_2}\cong-\frac{\omega_q}{v_{y1}}\frac{\partial n_{k_1}}{\partial k_{y1}}$. After integration of equation (5) over the wave vectors $\mathbf{k}_1$ and $k_{y2}$ one can obtain the following expression for the decrement of the surface plasmons:

$$\gamma = -\frac{\omega_b^2 q v_0}{\omega_q^2}, \quad \omega_b^2 = \frac{4\pi e^2 n_{0b}}{m_0(\varepsilon_0 + \varepsilon_1)}. \tag{9}$$

However, the induced radiation processes dominate over the absorption ones under the condition $P_0^2/2m_0 >> \hbar\omega_q >> T$. In this case we obtain

$$\gamma = \frac{2n_{0b}\left|W_{k_1 q k_z}\right|^2}{\hbar^3} LVm_0\left(\frac{1}{k_+} - \frac{1}{k_-}\right), \tag{10}$$

where $k_\pm = k_0 \pm \omega_q/v_0$, $v_{y1} = v_0$.

This is due to the fact that the probability for the electron to pass to the state with a smaller energy exceeds the probability to pass to the state with a higher energy. In the former case the probability is proportional to $k_-^{-1}$. This mechanism of the instability of the oscillations takes place at the different inhomogeneous solid state structures: semiconductor superlattice [3], two-dimensional gas [4], and other [5]. In finding the increment (10) we put

$$n_k = (2\pi)^3 n_{0b}\delta(k_x)\delta(k_y - k_0)\delta(k_z).$$

Thus, when a directive electron beam crosses the boundary of a plasmalike media, the surface plasmons fade away if the conditions $P_0^2/2m_0 >> T >> \hbar\omega_q$ are met (classical case). However, at low temperatures, $P_0^2/2m_0 >> \hbar\omega_q >> T$ (quantum case), the radiation processes begin to dominate over the absorption ones and the surface oscillations grow up with increment

$$\gamma = \frac{2\omega_b^2 q v_0}{\omega_q^2}. \tag{11}$$

These processes are very important for the diagnostics of the surface of solids.

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